

## FIRST-YEAR PERFORMANCE OF THE CHORRERAS PV-HYBRID ICE-MAKING SYSTEM IN CHIHUAHUA, MEXICO

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### ABSTRACT

This paper describes the reliability and performance of the Chorreras photovoltaic (PV) hybrid ice-making system. The system is a first of its kind in the world and is located near the fishing village of Chorreras, which is located along a man-made lake in a remote desert area of the State of Chihuahua in northern Mexico. The information gathered from technical field visits and a GOES satellite-based data collection system are reviewed to discuss system design and operation. The system has been working well in producing ice on a daily basis with only some minor control problems and water line calcification that reduced ice production until the line was cleaned. The hybrid system provides a daily average of 8.9 kWh at 240 volts to the ice-maker. The system Coefficient of Performance (COP) is about 0.65 and a total of 97 percent of the energy has been supplied by the PV array, while only 3 percent has been supplied by the back-up propane-fueled generator. Production of ice varies slightly each month due to changes in insolation and ambient temperatures. Overall ice production averages about 85 kg of ice per day. This project and this paper are dedicated to the memory of Ing. Juan José Oñate Rodríguez from the Dirección General de Desarrollo Rural, who was the original project developer for the State of Chihuahua.

### INTRODUCTION

The world's first automatic commercial PV ice-making system was installed in March 1999 to serve the fishing community of Chorreras, Chihuahua. The Chorreras ice-maker system was designed and installed by SunWize Technologies of Kingston, New York, with the assistance of Energía Solar de Ciudad Juárez (ENSO) from Chihuahua. This project was possible due to the support of developing high-value renewable energy applications provided by the New York State Energy Research and Development Authority (NYSERDA), which had teamed with Sandia National Laboratories (SNL), the State of Chihuahua Dirección General de Desarrollo Rural (now Secretaría de Desarrollo Rural), and the Southwest Technology Development Institute (SWTDI) at New Mexico State University to develop,

install, maintain, and monitor a PV hybrid ice-maker. The project was done in coordination and with cost-shared funding assistance from the Mexico Renewable Energy Program sponsored by the U.S. Agency for International Development (USAID) and the U.S. Department of Energy (DOE).

In the middle of the Chihuahuan desert lies the Luis Leon Reservoir formed from the waters of the Rio Conchos as seen in Figure 1. For over a quarter century, fishermen from the nearby community of Chorreras have fished this man-made lake for bass, catfish, tilapia, sunfish, and carp. Today, there are about 70 fishermen who make a reasonable living from the lake. The community is not serviced by the conventional electric grid, and it is nearly a four-hour drive from the lake to Chihuahua City to get the fish to market. Thus, the fishermen have had to rely on Chihuahuan wholesale merchants to come and purchase fish from them.



**Figure 1. The Luis Leon reservoir in the heart of the Chihuahuan desert with the Chorreras ice-house.**

The fish buyers often bring some ice when they purchase fish and often barter the value of ice for fish. However, the buyers do not always show up when they say they will, and the fishermen of Chorreras sometimes have lost fish to spoilage due to lack of ice. The fishermen also end up paying relatively high rates for the trucked-in block ice from Chihuahua when it does show up. The fishing cooperative annually harvests about 80,000 kg of fish. However, with no local ice source,

they have had to put off fishing or take their chances that ice will arrive on time. The lack of ice also limited their ability to independently sell their fish, particularly during the high demand season of Lent in the spring.

Recognizing this problem, the State of Chihuahua and Sandia joined forces to install a renewable energy powered ice-making system. The goal was to install an on-site ice-maker that could adequately meet ice needs. In response, SWTDI set up a solar and wind resource monitoring system for Sandia in 1995 to verify the renewable resources. While the initial concept was to install a wind-powered ice-making system, the wind resource was deemed inadequate with an annual average windspeed measured of only 3.5 m/s (SWTDI, 1999). Thus, the concept for powering the ice-maker from PV came to the forefront with an average annual solar resource of about 6 kWh/m<sup>2</sup>/day.

However, the project turned out to be even more challenging than expected. Significant technical hurdles had to be overcome to develop a viable ice-making system that was energy efficient. Figure 2 shows the PV ice-making system that was developed and installed in Chorreras by SunWize and ENSO. This system has eliminated dependence on fish buyer ice deliveries and in losing fish due to spoilage. Most ice-making is done with the PV system and the propane generator is used only sparingly for extended cloudy periods which are relatively rare in this desert climate.



**Figure 2. End-user training on the Chorreras PV hybrid ice-making system in Chihuahua, Mexico.**

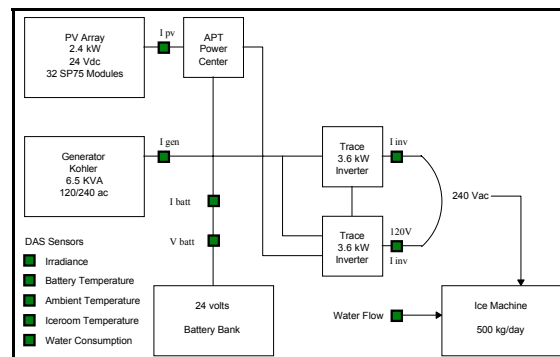
### ICE-MAKING SYSTEM DESIGN

The concept of solar-powered ice production in the remote desert is not a trivial one. High solar insolation certainly maximizes ice-making potential, but likewise high ambient air temperatures of over 40°C in the summer also reduce that potential. The northern Chihuahuan desert has high summer ambient temperatures, as well as winter temperatures well below freezing, which is an abusive environment for batteries. These considerations led to some interesting design and operational challenges. Finding an acceptable freshwater source was another challenge since the fishermen wanted to be able to use the ice for personal use as well. This desire eventually resulted in the community building a 7 km gravity flow aqueduct across the rocky desert ground from a clean spring water source.

The PV hybrid system is built on a galvanized steel frame bolted on a concrete platform and consists of the following major components:

- 2.4 kW PV array (fixed 30° array tilt) with 32 Siemens SP75 solar modules;
- Ananda Power Technologies (APT) Power Center;
- 24 Vdc 2200 Ah battery bank with 2 V cells;
- Two Trace Engineering 3.6 kW modified sinewave inverters provide 240 Vac electricity;
- One Kohler 6.3 kW propane fueled generator.

Figure 3 is a one-line diagram of the complete PV hybrid ice-making system. The propane-fueled generator was included in the design to provide backup battery charging and boost ice production when needed for larger fish hauls and/or cloudy weather. Operation is controlled automatically through inverter set points. The batteries absorb high current transients and allow for load shifting to nighttime for more efficient summertime ice production when cool ambient temperatures are favorable for maximum ice production. The battery bank is thermally insulated and uses dc fans for cooling and hydrogen venting. Two Trace modified sinewave inverters are stacked together to deliver 60 Hz, 240 Vac single-phase power for the icemaker.



**Figure 3. System one-line diagram. The square markers indicate SWTDI data acquisition sensors for measurements.**

Figure 4 shows the system power center and inverters. The inverters provide power to the icemaker. The ice-maker is a vertical-evaporator compression-cycle unit installed on the roof of the fish storage building. It was designed for low maintenance and high reliability. For this specific application, modifications were made to the Chorreras ice-maker to reduce power consumption. A smaller compressor and condenser heater was modified resulting in a reduced current from approximately 22 to 11.5 amps at 240 Vac, thus reducing power requirements by about 40 percent. A 7 km aqueduct was installed by the Chorreras community to the fish storage facility to provide high-quality water. The polypropylene pipeline was buried 0.3 m in the hard desert rock soil to help provide lower water supply temperatures. Approximately 1.5 km from the ice-maker stands a 10,000-liter storage tank on top of a hill that provides consistent

gravity water flow with sufficient pressure for the ice-maker (Hoffstatter, 2000).



**Figure 4. System Trace DR series inverters and APT power center with disconnects.**

The ice-maker is set to run a dozen or so 15-minute automatic ice-making cycles each day (about 3 hours a day). The system freezes the water, a crusher breaks the ice into convenient flakes, and the ice falls via gravity into a cold storage room. The PV system typically produces about 80 to 90 kg of flake ice per day. However, production of ice can be increased by manual operation of the generator allowing a maximum ice production capacity of more than 400 kg/day. The timer is set to provide no ice on Sundays (a day with minimal fishing) to allow the PV array to fully charge the battery bank and help equalize the batteries each week.

### DATA ACQUISITION SYSTEM

A data acquisition system (DAS) was designed, built, and installed by SWTDI for Sandia and SunWize to monitor system performance. The DAS was installed in March, 1999 and uses a GOES-based satellite communication system for the remote site. The DAS consists of a Campbell Scientific CR-10X Datalogger, electronic transducers, and an assortment of other sensors. The DAS is used to measure several environmental and system parameters including the following:

PV current	Generator current
Generator run-time	Battery temperature
Battery voltage and current	Inverter DC current
Load current and voltage	Ambient temperature
ice room temperature	Plane of array insolation
and water flow	

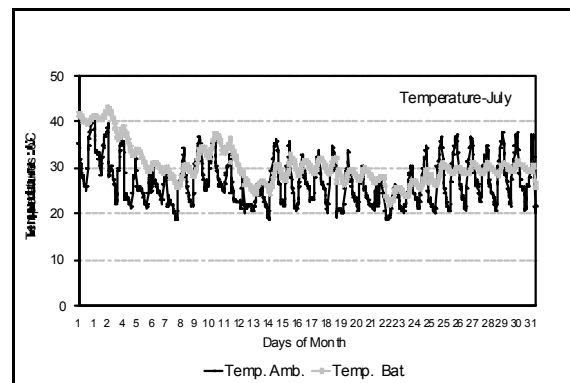
The stored data is hourly averaged and transmitted every four hours via the GOES satellite. Monthly data reports allow the project team to monitor system performance and identify any potential problems.

### SYSTEM RELIABILITY

The ice-maker is set to operate during the cool, late-night hours during the summer since high ambient and water temperatures reduce system ice-making efficiency. The load is driven solely by the batteries at night while the PV array replaces the consumed energy during the day. This nighttime operation results in deep-battery

discharge cycles and increases ice production. In the winter, the system is used to produce ice during the daylight hours, allowing the PV array to provide some energy, directly minimizing battery roundtrip efficiency losses and extending battery lifetime due to decreased cycling.

The system has successfully operated in an unattended mode for over a year since its installation with only a few minor glitches observed. While the system has typically operated on most of the scheduled days, there has been some small variation of ice production due to control system instability during the shifting of the ice-maker from ice production to ice harvesting cycles. During the first three months of production, ice making cycles were inconsistent yielding only a daily average of 80 kg of ice. Adjustments to the compressor and modifications on the control timer corrected the inconsistency resulting in a daily average of 90 kg afterwards. In addition, the load surge currents, normally handled by an electric grid, resulted in failures of some control components and system shutdown for approximately 20 days in July, 1999. Repairs were made but the system did not operate for several days in early August when the generator ran out of fuel, consequently allowing battery voltage to drop to the point where the inverters automatically shut down the load. Inverter operation resumed after two days; however, the system remained unnecessarily off-line for additional days because the users did not realize that a reset switch had to be thrown. Daily, weekly, and seasonal weather differences results in variations in the generator run time. During the longer summer days, generator operation is more infrequent. During the first 14 months of operation, the generator provided only 3 percent of the total energy used.



**Figure 5. Ambient and battery temperatures for July, 1999. Note how battery temperature dropped when additional venting was added.**

The batteries are enclosed in a thick-walled, insulated industrial plastic enclosure filled with water and baking soda; however, temperatures in excess of 45° C (hourly average) were recorded while the batteries were being charged. The original passive cooling vents and a small hydrogen vent fan were not cooling the batteries sufficiently after installation. However, a dc cooling fan was added in July, 1999 to the battery container which

remediated high battery temperatures and kept the battery bank below 40° C (Estrada, 1999).

continuously, while supplying power to the ac load and the DAS.

### SYSTEM PERFORMANCE

Table 1 summarizes the energy performance of the system from April 1999 – May 2000. The PV array supplied a total of 3,542 kWh (253 kWh monthly average) of energy; the generator delivered a total of 115 kWh of energy. The total energy input to the system (PV plus generator) was 3,657 kWh over the 14 months.

The ac load (ice-maker) consumed a total of 2,075 kWh allowing for an overall system efficiency (energy-out/energy-in) of 57.4 percent. Figure 6 illustrates the system's energy production and consumption. The battery performance for the first 14 months of operation was found to provide a 50 percent round-trip efficiency (discharging to charging ratio). Both inverters run

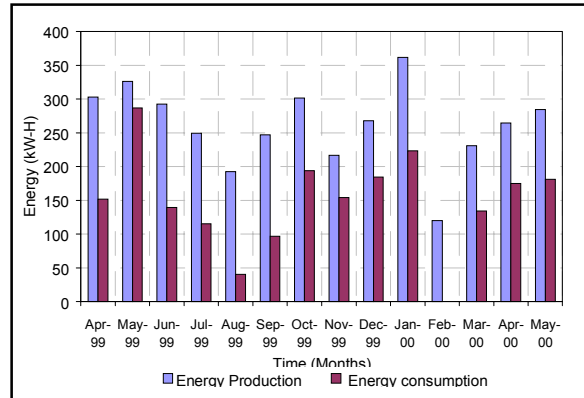


Figure 6. First year system energy performance

Table 1: System energy balance data

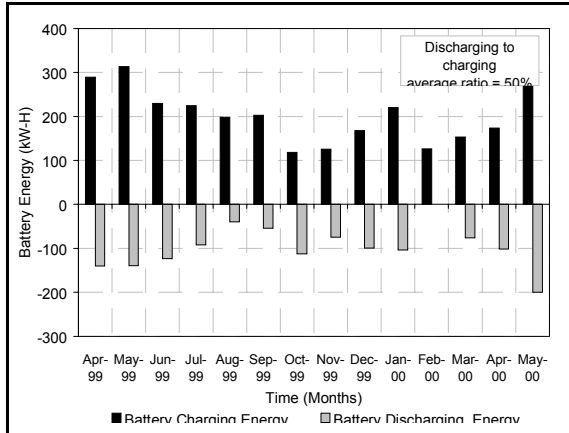
Period	PV array Energy (kWh)		Generator energy (kWh)		Load (kWh)	Losses (kWh)	System efficiency
	Total	%	Total	%	Total		(%)
April-99	278.5	91.8	24.3	8.0	151.7	151.1	50.1
May-99	326.1	100	0	0	286.6	39.5	87.8
June-99	232.0	79.4	60.2	20.6	139.3	152.9	47.6
July-99	219.2	87.9	30.0	12.0	115.3	133.9	46.2
Aug-99	192.6	100	0	0	40.3	152.4	20.9
Sept-99	246.7	100	0	0	96.8	149.9	39.2
Oct-99	301.6	100	0	0	194.0	107.6	64.3
Nov-99	216.7	100	0	0	154.2	62.5	71.1
Dec-99	267.6	100	0	0	184.5	83.1	68.9
Jan-00	361.5	100	0	0	223.0	138.5	61.6
Feb-00	119.8	100	0	0	0	119.8	0
Mar-00	230.7	100	0	0	134.4	96.4	58.2
April-00	264.7	100	0	0	174.8	89.9	66.0
May-00	284.5	100	0	0	181.0	103.5	63.6
Totals	3542.2		115		2075.9	1580.0	
Avg.		97		2.9			57.4

Table 2 summarizes first year battery performance data. The roundtrip battery bank efficiency (discharging to charging ratio) was steady throughout the first year indicating little to no change for overall battery bank capacity. Note for some months the system was off-line for several days and efficiency is not calculated. Figure 7 summarizes the energy into and out of the battery bank.

Table 2: Battery performance data

Month	Avg. Bat voltage	Chrg Energy (kWh)	Dischrg Energy (kWh)	Round trip energy % efficiency
Apr-99	25.9	289.3	-140.0	48.4
May-99	26.3	312.8	-139.5	44.6
Jun-99	26.1	229.2	-123.4	53.8
Jul-99	26.3	224.4	-92.1	-
Aug-99	25.8	198.1	-39.4	-
Sep-99	26.5	203.0	-54.5	-
Oct-99	25.9	118.3	-112.1	-
Nov-99	26.0	125.3	-74.5	59.3
Dec-99	25.7	168.0	-99.6	59.2
Jan-00	26.2	220.0	-103.8	47.2
Feb-00	26.8	126.4	-0.0	-
Mar-99	26.3	153.6	-79.4	49.4
Apr-00	25.7	173.4	-101.2	58.4
May-00	25.6	343.9	-200.0	58.3





**Figure 7. Battery charging and discharging performance.**

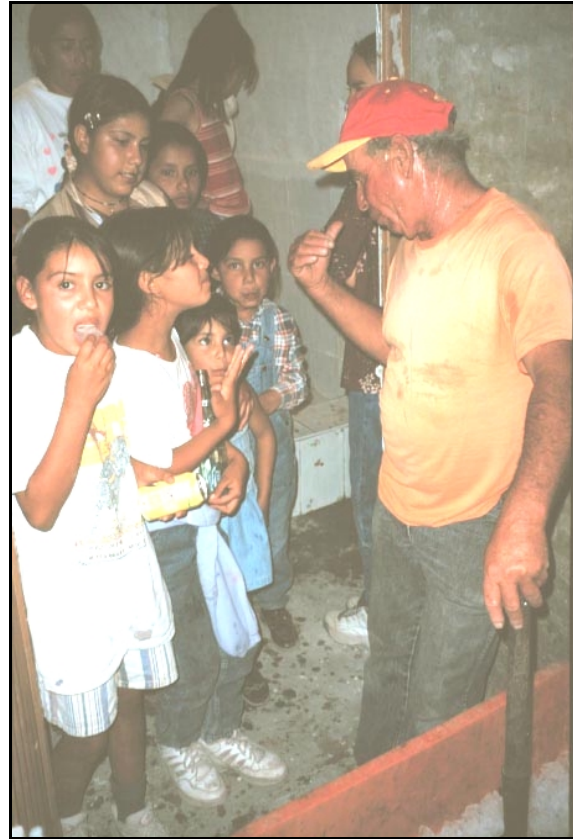
From April to October 1999, the ice-maker yielded an average daily ice production of 85 kg per day, mostly from solar energy. Gradual calcification of the ice-maker water pipes eventually caused one of the nozzles to become clogged to the point of spraying some water throughout the ice-maker cabinet, which caused one of the two-evaporator contractors to start to hum. The noise concerned the users who shut down the system in February, 2000. Upon a March spring maintenance visit by SunWize, a mechanical cleaning of the system identified and corrected the problem and the system was brought back to normal operation (Hoffstatter, 2000). A simple (acidic) rinse provided the chemical cleaning necessary for the pipes. The end-users have been trained how to conduct a vinegar rinse (about once every six months).

### ECONOMICS OF THE SYSTEM

The State Government of Chihuahua purchased the ice-making system for US\$38,000 with cost-share assistance from Sandia and USAID. In addition, the State of Chihuahua and the community of Chorreras pitched in additional funds to build the 7 km aqueduct and to rehabilitate the ice-room. NYSEDA funded engineering design and development for this novel system, and Sandia funded the DAS and follow-up system monitoring. Thus, the final cost for this project was about US\$150,000. However, the value of the now commercialized PV ice-maker unit is about US\$50,000.

Ice production has been found to be about 11.5 kg per sun hour with an overall COP of about 0.65. The system can produce over 25,000 kg of ice per year from the solar alone. Assuming a value of US\$0.30 per kg of ice (for this remote site where it must be hauled in), this implies that a simple payback for the ice-making system is under 7 years. Taking into account the value of reduced fish spoilage, actual payback is actually well under 5 years for the PV ice-maker. Overall, it is anticipated that ice production over the system lifetime, with future battery replacements and system maintenance, should be about US\$0.15 per kg (Foster, 2000). Of course, having a reliable source of ice in the desert for a cold drink has an

intrinsic value that is difficult to express simply in terms of dollars and cents, as demonstrated in Fig. 8.



**Figure 8. Chorreras residents enjoying local ice from the Chorreras PV ice-maker.**

### CONCLUSION

In the first year of operation the ice-maker has performed well. A few relatively small changes in equipment and operation have resulted in consistent ice production using mainly solar energy. A simplified regular maintenance procedure for chemical cleaning to prevent calcification was developed and taught to the system users. Overall, the system has averaged about 85 kg of ice production per day for the first year.

It is important to include thermal consideration in the design of battery racks or containers. Even small thermal differences among batteries can contribute to battery decay in the long-run. A strict maintenance schedule and procedure is required for batteries that pays special attention to safety. This schedule includes adding water and monitoring battery temperature and voltage. In periods of low insolation (winter with short days, or cloudy seasons) consideration might be given to adjusting the inverter set points to allow longer generator run times. Manually initiated frequent (monthly) equalization periods are also recommended. Efforts continue to expand on the maintenance program to enable the system users to maximize the life and productivity of this unique system.

Finally, for any type of relatively complicated hybrid system, it is important to not only consider the technical

side of the equation, but the institutional side as well. The system has proven that a properly designed, operated, and maintained system can indeed produce a significant and valuable resource, such as ice, even in the middle of the desert. However, such a successful system requires local buy-in and follow-up, and a complicated system such as this if it was simply "parachuted in" would soon not be functioning due to relatively minor problems that require an experienced technician to solve. Long-term commitment and follow-up by the project partners is required for project success. This project is a good example of using renewable energy as a tool to contribute to local economic development in a remote area.

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Figure 9. The Chorreras community at the inauguration of their 2.4 kWp PV ice-making system in March, 1999. Everybody appreciates a little extra shade in the desert.